Design Parameters for Lateral Vibration of Multi-storey Timber Buildings

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1 Introduction

Timber buildings are now reaching heights at which their lateral dynamic response to wind load is an important consideration in design, and such dynamic effects are particularly important in timber buildings because they have low mass, and they may have relatively flexible connections. The 14-storey Treet building in Bergen, Norway recently became the tallest habitable timber building, and has a total permanent load of 135kg/m^3 (Magne Aanstad Bjertnæs (Sweco), personal communication). This compares with a typical value of 300kg/m^3 for a tall building in concrete (Yang et al. 2004), and 160kg/m^3 in steel (Huang et al. 2007).

Wind-induced vibration may cause discomfort to building occupants or otherwise impair the serviceability of the building. In low-mass structures, it is possible to reduce vibration by changing other parameters: primarily by increasing damping or natural frequency. In steel or reinforced concrete buildings, this may be done by increasing member sizes or adding supplemental damping devices, and such interventions may be necessary in timber construction. Timber is a relatively new material in large multi-storey construction, however, and accurate design guidance specifically for multi-storey timber buildings, particularly for damping, would mean that designers would not be forced to use over-conservative assumptions.

The Eurocodes currently give no guidance on damping ratios for lateral vibration of multi-storey timber buildings. Eurocode 1 Part 1-4 (BSI 2005) gives damping ratios for various materials and structural forms, however the only entry relevant to timber construction is a range of values for timber bridges. There has been a shortage of empirical evidence for the natural frequencies and damping of these buildings in their complete form, but in recent years, some such measurements have been presented in the literature.

A six-storey brick-clad light timber frame building, built in the controlled environment of a former aircraft hangar, is tested using ambient and forced vibration methods by Ellis & Bougard (2001). The use of large cross-section engineered timber elements has subsequently allowed taller construction, and research has started to characterise their dynamic behaviour. Omenzetter et al. (2011) measure the heavy timber frame NMIT building in New Zealand, primarily with an interest in predicting its seismic performance. Hu et al. (2014) present dynamic properties from ambient and forced vibration tests on multi-storey buildings in glued-laminated timber (glulam) and cross laminated timber (CLT) in North America. Reynolds et al. (2014; 2015; 2016) present a series of measurements on cross-laminated timber and light timber frame buildings in the UK, Italy and Sweden, which are included in the present study, all measured using ambient vibration methods.

Results from tests on a 3-storey light timber frame building in Switzerland, by Steiger et al. (2015), show the relationship between forced and ambient vibration tests, which is important given that almost all the data on taller buildings is based on ambient vibration measurements. They show that the ambient vibration tests, at much lower vibration amplitudes of vibration than the forced vibration tests, give lower measurements of damping, and slightly higher measurements of natural frequency. It is reasonable to assume that this is due to a genuine variation of damping with amplitude, rather than inaccuracy in either method. Feldmann (2015) investigates the dynamics of timber towers and multi-storey timber buildings ranging from a 20m-tall multi-storey building to a 100m-tall CLT wind turbine tower.

This body of work means that it is now possible to start to use data on the response of completed buildings to make predictions during design.

In the present study we bring together measurements of the dynamics of multi-storey timber buildings taken over the past four years. Starting with the raw data in each case, we process the data using a common methodology to create a compatible set of measurements of natural frequency and damping, which is then used to discuss appropriate design methods.

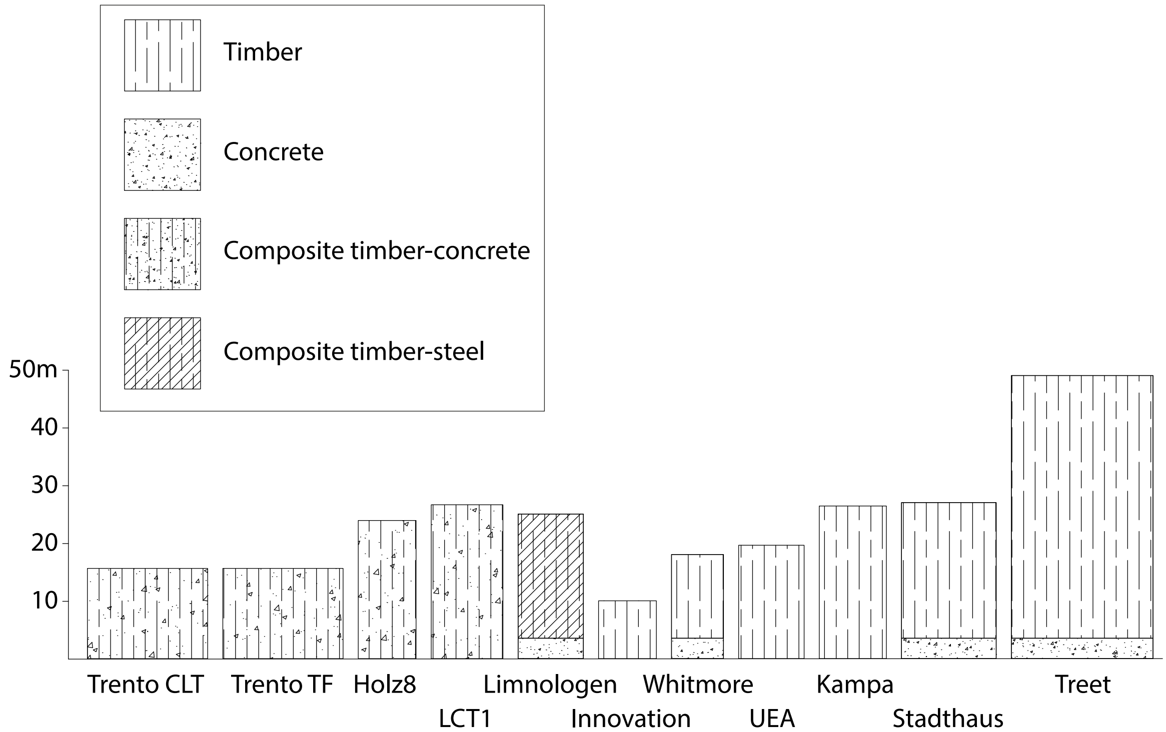

Figure 2.1. Building type, with height and along-wind dimension shown to scale for each of the measured multi-storey timber buildings.

2 Method

In-situ dynamic tests were carried out on 11 multi-storey timber buildings in Central Europe and the UK, relating their natural frequencies and damping ratios in the fundamental mode of vibration in each significant lateral direction.

The buildings are illustrated in Figure 2.1, which shows their construction type and, to scale, their height and their more slender along-wind dimension. They are described as timber, concrete, steel or composite buildings according to the classifications proposed by Foster et al. (2016). We will not reproduce the criteria for classification here, but note that they consider the materials forming the main vertical and lateral load resisting structural elements. Steel used in connections in timber structures and, to some extent, floor materials are not considered to change the classification of a building. The timber in these buildings includes cross-laminated timber, glued-laminated timber and light timber frame structural systems.

Each building was tested using ambient vibration methods. Accelerometers were placed on a part of the structure expected to move in the first few modes of vibration of the building, and a time-series of data, typically approximately 30 minutes in duration, was recorded as the building moved under the ambient wind load. Established modal analysis techniques could then be used to extract modal properties from the data.

We assessed the variation of natural frequency and damping ratio with amplitude. This consideration was important, since modal properties of buildings have been observed to vary substantially with amplitude over the range of excitation imposed by wind. Following the derivation of Jeary (1992), the variation in modal properties with amplitude of vibration can be analysed using the random decrement technique. The amplitude under consideration was expressed as the magnitude of the random decrement threshold used to calculate the modal properties. Since, in the random decrement technique, any contribution from a sinusoid with amplitude greater or less than the threshold level averages to zero, what remains is the decaying sinusoid at a given amplitude (Jeary 1992).

For each building, the variation of modal properties with amplitude was investigated. A slight variation of natural frequency with amplitude was observed, along with a much stronger variation of damping. This observation is common in the lateral vibration of tall buildings, and is attributed to the mobilisation of more and more frictional damping mechanisms as amplitude is increased (Spence & Kareem 2014).

Given this variation of frequency and damping with amplitude, it was necessary to define a reference amplitude to use for comparison of the buildings. Reviewing research and design guidance from around the world on design for human comfort under wind-induced vibration, Burton et al. (2015) state that accelerations below 5mm/s^2 are considered unlikely to cause “adverse occupant response”. The damping measured at this amplitude would be accurate at this transition point, and also be a conservative estimate for higher amplitudes. 5mm/s^2 would therefore be a useful reference amplitude for design.

This acceleration was rarely exceeded, however, in the measured data for these buildings, and so it was not possible to assess the modal properties at this amplitude for all buildings. A lower reference value of acceleration was chosen to give comparable data for each building, as shown in Table 2.1. This amplitude was measured at a the point in the structure expected to move most in the fundamental mode, generally at the outer edge of the roof or the top floor of the building.

A reference acceleration of 1mm/s^2 was chosen. For most of the buildings, this threshold was crossed sufficient times to give repeatable estimates of natural frequency and damping using the random decrement technique at or near 1mm/s^2. It is noted that, in future work, long-term monitoring of buildings could yield sufficient data at higher amplitude to make an estimate of properties at the higher amplitude.

The geometry of each building considered here is given in Table 2.1, along with the reference amplitude of acceleration used for comparison of measured natural frequency and damping. In Section 3, we look for a correlation between these modal properties and building parameters that could be used in the design process.

Table 2.1 Building data.

Building	Modes	Height (h) (m)	Along-wind dimension (l) (m)	Slenderness (h/l)	Reference amplitude (mm/s^2)
Trento CLT	1	15.6	20.8	0.75	1.0
Trento Frame	1	15.6	20.8	0.75	1.0
UEA Student residence	1	19.6	11.3	1.73	1.0
Treet	1,2	49	24.5	2.00	0.9
Limnologen	1	25	11.3*	2.21	1.0
Murray Grove	1	27	16.4	1.65	0.9
Whitmore Road	1	18	9.0	2.00	1.0
BRE Innovation park	1,2	10	10.0	1.00	0.5**
Holz8	1	23.9	10	2.39	0.9
Kampa	1,2	26.4	11.6	2.28	1.0
LCT1	1,2	26.6	12.4	2.15	1.0,0.9

* This building has two steps in plan dimension, so an average dimension was used.

** The amplitude of vibration for this building was insufficient to estimate the modal properties at $1mm/s^2$, so values for a lower amplitude are stated.

The natural frequency of a building depends only on its geometry and its distribution of stiffness and mass. If the buildings have a similar mean density of mass, and have a lateral stiffness designed to achieve similar displacement criteria, then their natural frequency varies predominantly with their height. A reasonable correlation between height and natural frequency in completed buildings has been shown (Satake et al. 2003), and this correlation is used in the simplified method given in Eurocode 1 Part 1-4 (BSI 2005).

Damping, on the other hand, derives predominantly from friction and very small-scale plastic behaviour, and has proved much more difficult to correlate with any easily measureable parameter. Measurements of over 200 buildings are presented by Smith et al. (2010), and fitted curves for damping against height have coefficient of determination (R^2) below 0.5 for each group of data (steel, reinforced concrete and hybrid steel-reinforced concrete buildings).

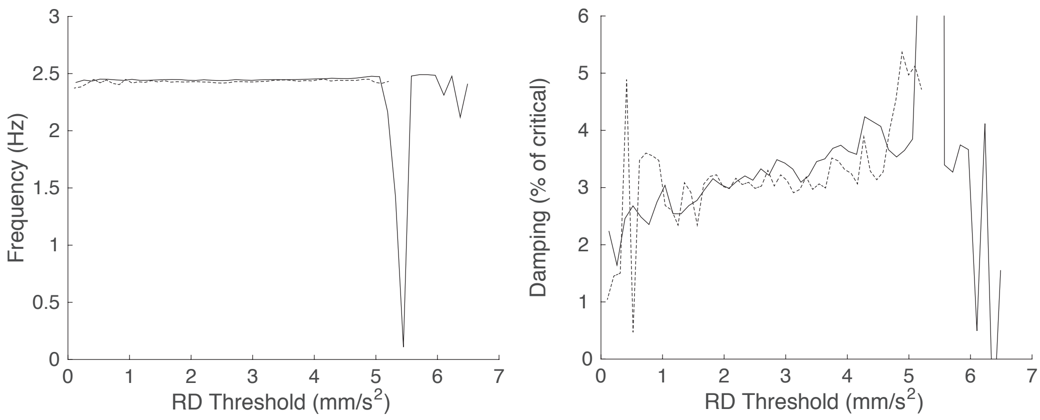

Figure 3.1. Variation of natural frequency and damping with amplitude for the UEA student residence measured in two separate tests to show repeatability.

There is some evidence in the literature that the stockiness of the building may provide an indicator of structural damping. Spence & Kareem (2014) include slenderness as a parameter in their model for damping variation in structures, and Jeary (1986) shows a correlation between the along-wind dimension of the building and the damping.

3 Results and Discussion

For each building, for the measurement point and direction which moved most, the natural frequency and damping ratio of the mode in question could be calculated for a range of random decrement (RD) threshold levels, corresponding to a range of excitation amplitudes. The results of this analysis for the UEA student residence are shown in Figure 3.1. Two lines are drawn, based on data measured on two separate occasions at the same location on the top floor of the building. It can be seen that the results for both natural frequency and damping are repeatable between the two tests over a certain range of amplitudes, in this case between approximately $1mm/s^2$ and $5mm/s^2$.

The measurements on this building were exceptional in that they were taken during high winds, with a 3-hour peak gust of 17m/s recorded at a nearby weather station. This meant that a substantial variation in damping was evident over the range, whereas buildings measured in lighter winds often showed an approximate plateau in damping measurements.

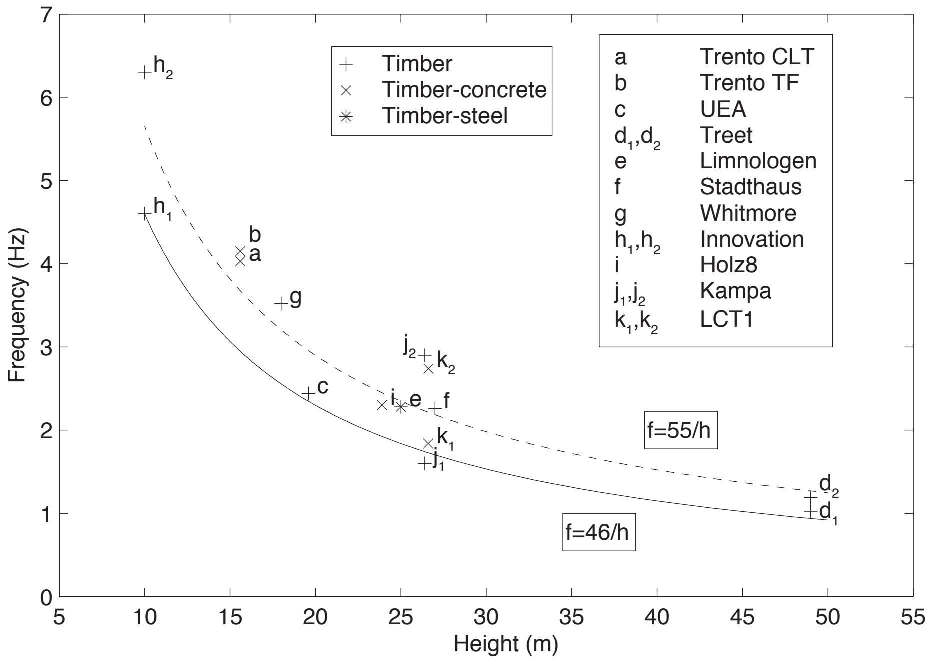

Figure 3.2. Relationship between frequency and height for all buildings.

All the buildings considered in the present study either followed a gradual increase in damping with amplitude, as shown in Figure 3.1, or an apparent plateau with variation less than the random variation of the measurements.

Figure 3.2 shows the relationship between natural frequency and height for the measured multi-storey timber buildings. It shows a clear correlation of fundamental natural frequency with height, which suggests that it may be possible to allow estimation of natural frequency by a simplified rule in the absence of more detailed calculations. Such a rule is given in Eurocode 1 Part 1-4 (BSI 2005), which states that the natural frequency in Hertz of a multi-storey building can be estimated as $46/h$, where h is the height in metres, for buildings over 50m high. None of these buildings exceed 50m in height.

A curve based on this rule is plotted in Figure 3.2, and gives a reasonable conservative estimate of the fundamental natural frequency for these buildings. Applying a least-squares fit equation of this form gives f=55/h. It might be considered that, where this equation is used in design for serviceability, the better estimate given by the least-squares fit would be preferable over a conservative estimate.

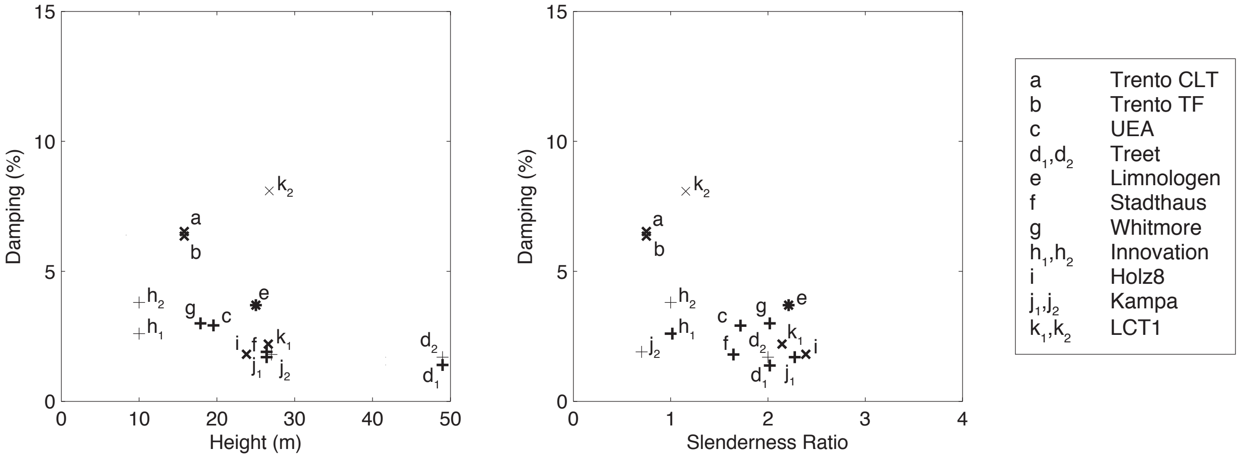

Figure 3.3. Relationship between damping and height or slenderness ratio.

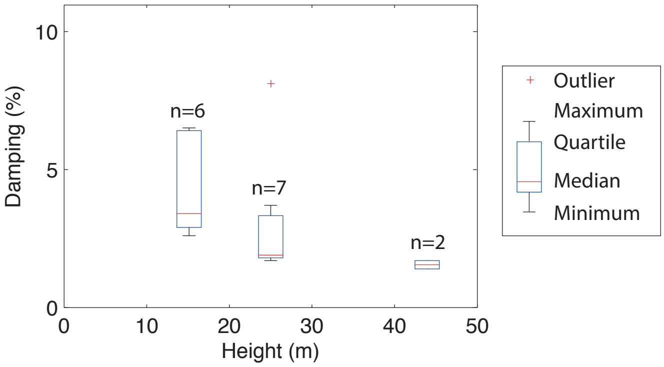

Figure 3.4. Variation of damping in 10m intervals of height.

Calculations based on the estimated natural frequency and damping of the structure can also influence the ultimate limit state design loads according to Eurocode 1 Part 1-4 (BSI 2005), through the dynamic factor. Calculation of this factor would require characteristic values of modal parameters. The low height and light weight of these buildings mean that there would be no increase in load due to dynamic factor, but for taller timber buildings this factor may become important.

Figure 3.3 shows that the relationship between damping and height is not so clear as that for natural frequency, although there is a tendency for damping to reduce with height, and there appears to be a reduction in the scatter of damping ratios with height. Figure 3.3 plots slenderness against damping. Again there is no clear correlation, but the second mode in the LCT1 building is less of an outlier in this case, perhaps suggesting that its high damping ratio may be due to the stockiness of the building in that aspect. What is clear is that the expected value of damping in a taller building is lower than that in a shorter one. This is brought out by classifying each building into a ten-metre range of height, as shown in Figure 3.4, and examining the distribution of damping for the modes in those buildings.

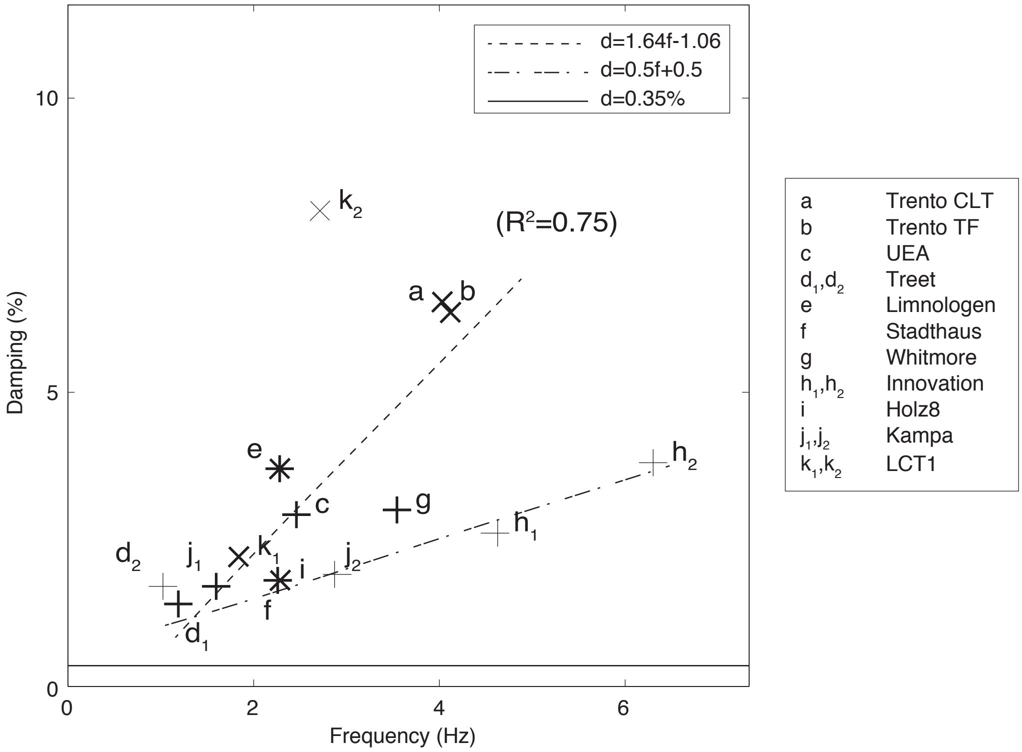

Figure 3.5. Relationship between damping and frequency. The Coefficient of Determination R^2 is given for the fit to the bold markers, which represent damping in the fundamental mode of buildings taller than 15m.

Another approach is to ignore any systematic variation of damping, so that the values can be described by their mean and standard deviation as a single population. This follows the current philosophy of Eurocode 1 Part 1-4 (BSI 2005), which specifies damping for structural forms independent of their geometry. The mean damping in these results is 3.7%, with a standard deviation of 2.5%.

Figure 3.5 shows the variation of damping with frequency in each mode for each building. There is perhaps some correlation evident here, particularly when only the fundamental mode of buildings taller than 15m is considered. These buildings are shown by the bold markers, and have some correlation with the equation shown in the figure. That relationship has two limitations, however: that it predicts damping below zero for frequencies below 0.65Hz, and that it greatly overestimates the damping for the shorter 'Innovation' building and underestimates that for the second mode in the 'Kampa' building.

For low frequencies, it may be that damping tends towards the value for the material damping of the timber, as the contribution of the structural system becomes dominant over that of non-structural elements. On this basis, a lower-bound for damping of 0.35%, given by the material damping in the timber itself (Yeh et al. 1971), might be appropriate. The lower relationship shown in the figure remains above the material damping of 0.35% at zero frequency, so appears reasonable for all cases.

There is no clear grouping of damping by building type. The composite timber-concrete buildings range from 2.2% to 6.4%, the composite timber-steel building has a damping of 3.7% and the buildings all timber above their first floor range from 1.4% to 5.6%.

4 Conclusion

The proliferation of multi-storey timber construction in the last decade means that a suitable dataset is now available to assess their dynamic performance, and draw conclusions that may be of use to designers. This paper collates dynamic measurements made by the authors, and draws out patterns of natural frequency and damping which may be useful in both preliminary and detailed design.

A high-level assessment is made of the correlation of these properties with relevant measurable parameters of the buildings, including their height and slenderness, as well as the correlation between natural frequency and damping. Design guidance could be based on a simplified relationship between these parameters, or could be founded in the fundamental properties of the system being used. More detailed calculations of natural frequency, for example, rely on knowledge of the stiffness of connections under serviceability limit state dynamic loads, and research is currently ongoing in this area.

The data presented here show that the simplified relationship between height and natural frequency for multi-storey buildings given in Eurocode 1 Part 1-4 (BSI 2005) of f=46/h, where f is frequency in Hertz and h is height in metres, is reasonable and conservative for this group of modern timber buildings. The existing f=46/h relationship is limited to buildings over 50m in height, which is higher than any of these buildings. A relationship of f=55/h is a more accurate fit for this set of buildings, and is therefore the one put forward in this case.

There is evidence of a variation of damping with natural frequency, height and stockiness, although there is a large scatter in each case, as is the case in measurements of damping in tall buildings in steel and reinforced concrete. A relationship of d=0.5f+0.5, where d is damping in per cent of critical and f is frequency in Hertz, is a lower bound for these buildings, and is realistic over a range of frequencies.

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